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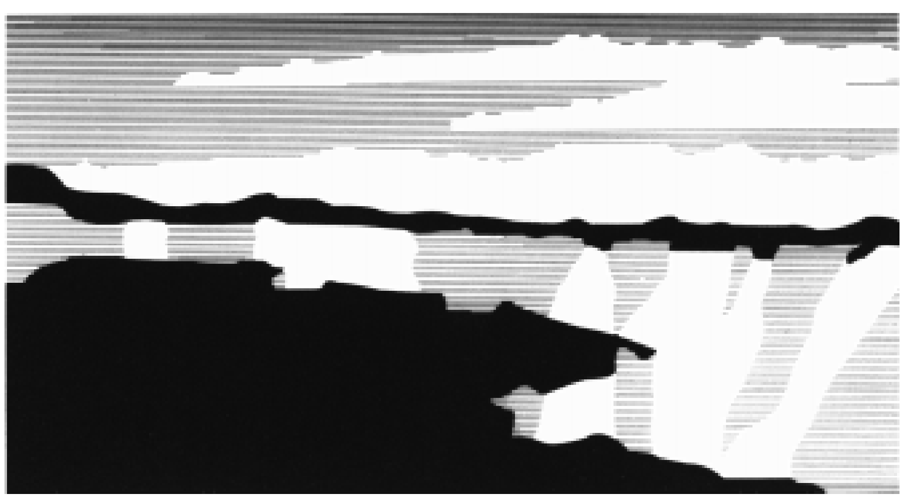

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GROUND MOTION CHARACTERIZATION OF THE SINGLE SHOT IN A MINING BLAST ARRAY WITH THE CLOSE-IN SEISMIC DATA

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Abstract Ground motion data from single, cylindrical explosions with the same source configuration as the individual explosions that make up a production mining blast array are analyzed. Strong shear motion is observed which can not be accounted for by the simple explosion source. Spall (the detachment and slap-down of the near surface strata and the separation of the burden and overburden from the continuum) and crack formation which accompany the explosion seem to play important roles in shear wave energy generation. The material anisotropy along the bench face can also be important. These shear energy may be the most damaging to the structures near the production site.

INTRODUCTION

Ground vibration has long been a major concern in the mining industry. Recently, it has attracted considerable attention in the explosion seismology community as well. A better understanding of the physical mechanisms of the ground motion generation from a mining blast will benefit the industry in tackling the near-by ground vibration problem as well as provide an understanding of more distant recordings (hundreds of kilometers) of these same explosions.

An industrial blast — mining or quarry blast in particular — is generally composed of an array of multiple shots fired in a time delayed pattern to maximize rock fragmentation and minimize ground vibration. The overall effect of a blast on seismic wave generation can in some instances be viewed as the time delayed linear superposition of the effect of each individual shot in the array (Stump and Reinke, 1988; Chapman *et al.*, 1992). Thus, the study of the single mining or quarry shot becomes the basic element for understanding the effects of multiple explosions.

EXPERIMENT AND DATA

A field experiment was conducted in a coal mine to obtain seismic data from single shots with the same configuration as those used in typical mining blasts. The test site was a shale bench in the coal mine roughly 150 meters wide and 11 meters high. The experiment was composed of 8 individual cylindrical explosions. All the explosions were located 6 meters from the vertical face of the bench. Shot configurations were all the same as shown in Figure 1 except for two shots in which

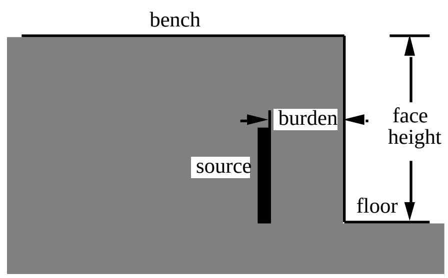

Fig. 1 Vertical cross section of the test shot configuration.

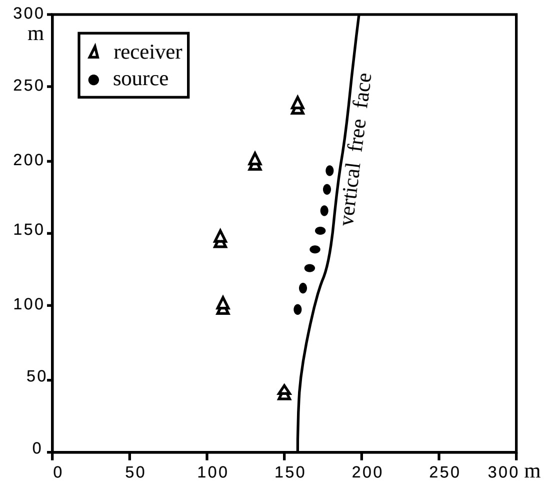

Fig. 2 Plane view of the test site and instrument layout.

there was an air deck above the charge. The shots were different only in explosive type and charge weight. Table 1 lists the characteristic shot parameters. The shots were detonated separately. During each shot, the bench face was cast into the pit and a crater was formed.

Table 1 Shot parameters*

shot number	charge depth† (m)	charge height (m)	charge weight (kg)	explosive type
1	4.6	1.2	78.47	ANFO
2	6.7	3.0	296.20	EMULSION
3	5.7	0.9	88.91	EMULSION
4	7.0	3.0	196.86	ANFO
5	6.0	0.9	58.97	ANFO ‡
6	6.6	0.9	88.91	EMULSION ‡
7	5.7	0.9	58.97	ANFO
8	7.0	3.0	296.20	EMULSION

* Radii of all the charge columns are 0.31 m.
† Charge depth is measured from the mid-point of the charge column.
‡ Charge with the air deck on top.

Ground acceleration data from these shots were recovered by an accelerometer array deployed on the bench behind the sources. There were 5 pairs of accelerometers, each consisting of a set of three component (vertical, radial and transverse) sensors buried just below the surface. The array covered a range from 48 meters to 157 meters from the sources and an azimuthal spread of 168° relative to the sources. Figure 2 shows the plane view of the experiment layout. Acceleration data were then integrated to ground velocity to reduce the medium inhomogeneity effect.

DATA ANALYSIS

Although the data were recorded in the very close-in range from the source, distinct seismic phases can still be separated and identified through comparison of the waveforms, record-sections and particle motion diagrams. Figure 3 shows a waveform record-section of the vertical component data. In addition to the first

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Fig. 3 A vertical component waveform record-section from the 8 shots.

Fig. 4 A typical particle motion diagram in the radial-vertical plane.

longitudinal P wave arrival, some secondary phases with slower velocity can also be discerned. Figure 4 is a typical particle motion diagram in the radial-vertical plane. The circle indicates the arrival of the P wave. The arrow points to the time when the ground motion changes from more vertical to a more radial orientation abruptly. This secondary arrival is probably the SV shear wave. Strong transverse waves, SH, are also observed in the data indicating the importance of possible secondary source effects.

As indicated in Figure 4, the SV shear wave energy is several times stronger than the longitudinal P wave energy. For the complete data set, the SV/P wave amplitude ratio ranges from 1.7 to 9.1. Although shear waves are predicted for a cylindrical explosion source, most of the theoretical models predict a SV/P amplitude ratio of less than 1. For the geological structure at this test site, the signal recorded by the sensors should have even smaller SV energy directly from the explosion. Figure 5 shows the evidence that bigger shots tend to have lower SV/P ratios. This fact and the abnormal SV energy indicate that the principal contribution to the SV generation might not come from the primary explosion source itself. A potential source responsible for the strong SV energy is spall. The original definition of spall is the parting of the near-surface layers due to the surface-reflected tensile elastic waves from an underground explosion with cratering explosion as a limiting case (Eisler and Chilton, 1964). In our case, spall includes both the parting of the near surface layers and the separation of burden and overburden from the continuum (Barker, *et al.*, 1993).

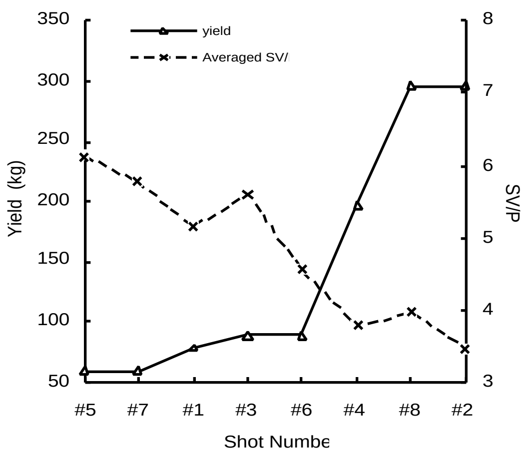

Fig. 5 The averaged SV/P ratio versus yield. Although there is some fluctuation in the data, the general trend shows that higher yield shots tend to have lower SV/P ratios.

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Fig. 6 P wave amplitude regression result in the logarithm domain. The regression plane is log(A)=1.90+0.94log(Y)-1.88log(R) where A, Y and R are defined in the text

Ground motion is related to the source-receiver range and the yield (presumably charge weight) in a power law model

$$A = 10^{a_0} Y^{a_1} R^{a_2}$$

where A is the ground motion amplitude, Y is the yield and R is the source-receiver range. In the logarithm domain, the exponents a_0, a_1 and a_2 are estimated with the linear regression method. Figure 6 demonstrates the result from P wave amplitude data . The exponent for the yield is 0.94. This value is different from the cube-root scaling in which the amplitude should be proportional to the cube-root of the yield (Langefors and Kihlström, 1967). On the other hand, the result is in accordance with some theoretical models (Mueller and Murphy, 1971). As is seen in Figure 6, data show little scatter about the regression plane. There is no appreciable difference in amplitude between the shots with and without air decks.

Seismic energy radiation pattern analysis is another way of characterizing the source. Amplitudes are measured from P, SV and SH waves separately. After range decay correction with the result from the regression analysis, the plots of the scaled amplitude against azimuth represent the radiation patterns for each phase. Figure 7 shows the energy radiation patterns for the P, SV and SH waves. The patterns are the averaged version from the 8 individual shots.

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Fig. 7 Amplitude radiation patterns of P, SV and SH waves. The crosses are the location of the sources. The dashed lines represent the bench face direction. Since no data were collected from the right side of the sources, the patterns just represent the left halves of the complete patterns.

It is seen that the P wave radiation pattern is very symmetric about the source. This symmetry indicates the azimuthal symmetry of its source. The SV pattern is not as symmetric. The asymmetry, inconsistent with the theoretical radiation from a vertical spall which is symmetric, might be due to the possible modification on the radiation pattern by the anisotropy of the medium along the bench face caused by previous blasts (Young and Hill, 1986; Reamer, 1993). SH waves show a consistent lobed pattern for different shots. This consistency indicates that SH waves were generated by a common mechanism. Several mechanisms can be responsible. Theoretical calculation shows that a vertical crack propagating horizontally along the bench face can generate SH waves (Knopoff and Gilbert, 1960); the horizontal spall of the burden may also be an important contributor and the material anisotropy can be strong enough too to induce SH motion (Mandal and Toksöz, 1991). All these possible mechanisms will generate SH waves with the similar radiation pattern observed.

SOURCE PROCESS

Based on the data analysis, the source process of the single shot explosion can be speculated. As the charge is detonated, the source can be thought of as a symmetric cylindrical explosion source. This source is primarily responsible for the P wave generation. As the gas pressure in the shot hole increases, the surrounding material fails and spalls. The vertical spall of the near surface strata and the overburden may greatly enhance the SV energy. The horizontal spall of the burden along with the crack formation will contribute to the SH wave generation.

CONCLUSION

Seismic data were collected in a controlled field experiment from several single cylindrical shots with the same configurations as those used in the production mining blasts. Regression analysis reveals that ground motion amplitude is proportional to the yield to the power of 0.94 for this particular data set. Strong shear wave energy was observed. This shear energy is probably a result of second source effect. The consistent SH radiation pattern implies a common generating mechanism maybe inherent to this kind of explosion source. Spall (horizontal and vertical), material anisotropy and crack forming are considered to be the important mechanisms in shear wave generation.

Since all the mining or quarry blasts are very shallow, the shear waves they generate may largely be trapped in the near surface layers. How to reduce the shear wave generation will be a major topic for ground motion control research.

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